

# Ion temperature anisotropy in the turbulent solar wind: Hybrid-Vlasov simulations

D. Perrone<sup>1</sup>, F. Valentini<sup>1</sup>, S. Servidio<sup>1</sup>, S. Dalena<sup>1,2</sup>, P. Veltri<sup>1</sup>

<sup>1</sup> *Dipartimento di Fisica and CNISM, Università della Calabria, I-87036 Rende (CS), Italy*

<sup>2</sup> *Bartol Research Institute, Department of Physics and Astronomy, University of Delaware, Newark, DE 19716, USA*

A natural laboratory to study plasma physics is represented by the solar wind, that is a turbulent plasma, almost collisionless, magnetized and, despite being highly ionized, approximately neutral [1]. It is composed of electrons, protons, alpha particles, that constitute only about 5% of the proton density, and tenuous populations of heavy ions.

The solar wind provides the only opportunity, for these types of plasma conditions, to be studied ‘in situ’. These measurements have shown that the ion distribution functions exhibit significant deviations from local thermodynamic equilibrium. Proton distribution functions commonly display a beam of accelerated particles along the direction of the ambient magnetic field [2]. Moreover, the alpha particles are observed to be heated and accelerated preferentially to protons [3, 4]. The acceleration of the solar wind and the spatial and temporal evolution of the ion velocity distributions represent nowadays unsolved problems. A key issue in space plasma physics is related to the identification of the physical mechanisms that produce energy dissipation at small scales. Kinetic effects are thought to be good candidates in playing this game.

In order to investigate the complexity of solar wind physics, a support from self-consistent, fully nonlinear Vlasov models is needed and a crucial tool is represented by kinetic numerical simulations. We present Vlasov numerical simulations of a turbulent, collisionless and magnetized multi-ion plasma, using a low-noise hybrid Vlasov-Maxwell code [5] in a five-dimensional phase space configuration (two dimensions in physical space and three dimensions in velocity space). Ions (protons and alpha particles) are treated as kinetic particles, so the Vlasov equation is solved for proton and alpha particle distribution functions, while electrons are considered as a fluid, using a generalized Ohm’s law [6], that retain Hall effects. The Faraday equation and the Ampère law, in which the displacement current is neglected, are integrated. An isothermal equation of state for the electron pressure close the system and the quasi-neutrality condition is imposed. All these equations are dimensionless and the characteristic quantities, used in the normalization, are the proton cyclotron frequency, the Alfvén speed and the proton skin depth [6].

The initial equilibrium configuration is modeled by a plasma composed by kinetic ions, with Maxwellian velocity distributions and homogeneous densities, embedded in a background mag-

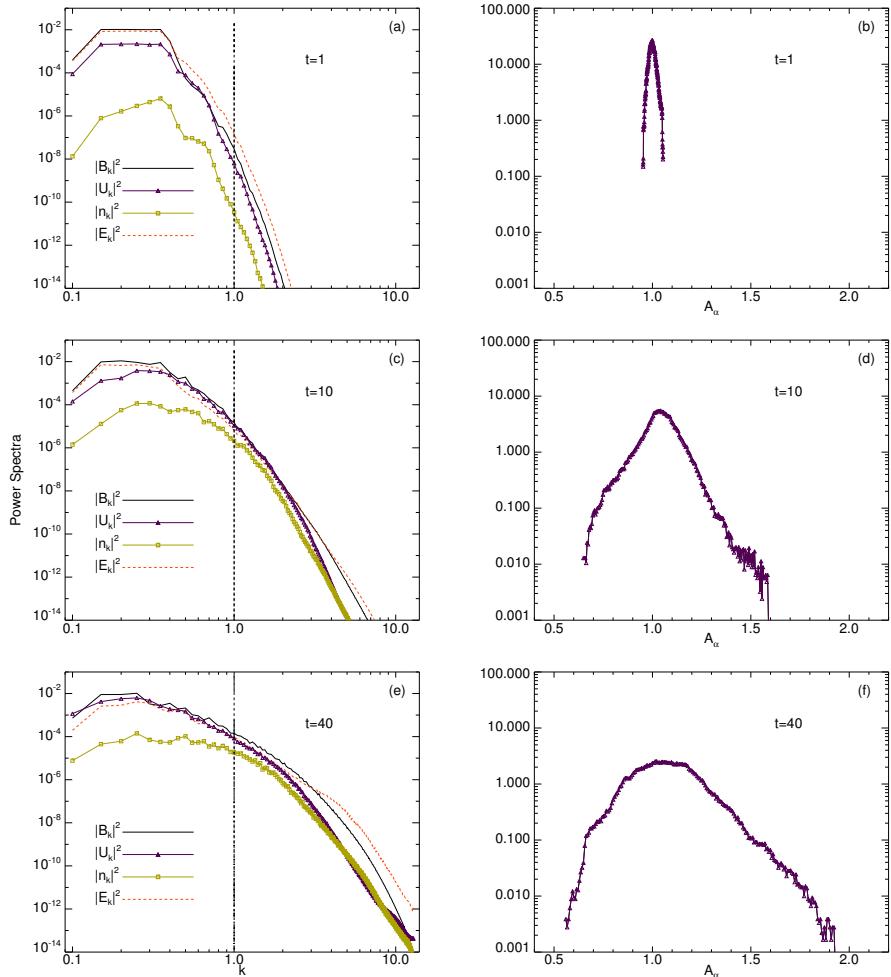


Figure 1: Left panels: Power spectra of magnetic (black-solid line) and electric (red-dashed line) fields, density (green-square line) and bulk velocity (purple-triangle line) of alpha particles for  $t = 1$  (a),  $t = 10$  (c) and  $t = 40$  (e). Right panels: PDFs of the temperature anisotropy  $A_\alpha = T_\perp^{(\alpha)}/T_\parallel^{(\alpha)}$  of alpha particles at the same times of power spectra:  $t = 1$  (b),  $t = 10$  (d) and  $t = 40$  (f).

netic field along the  $z$  direction. This configuration is perturbed by a 2D spectrum of Fourier modes, imposed for the magnetic field and proton velocity field. To avoid an artificial compressive activity, neither density perturbations nor parallel variance are imposed at  $t = 0$ . Energy is injected with random phases and wavenumbers in the range  $0.1 < k < 0.3$ , with  $k = 2\pi m/L$  (being  $2 \leq m \leq 6$  and  $L$ , the box size in both spatial direction). The rms of the initial magnetic perturbations is  $\delta B/B_0 \simeq 0.3$ . The value for the proton plasma beta is fixed at 2, consequently the proton thermal speed is 1. For the alpha particles, we fix realistic values for the solar wind conditions. Moreover, the electron to proton and alpha particle to proton temperature ratios are both fixed at 1.

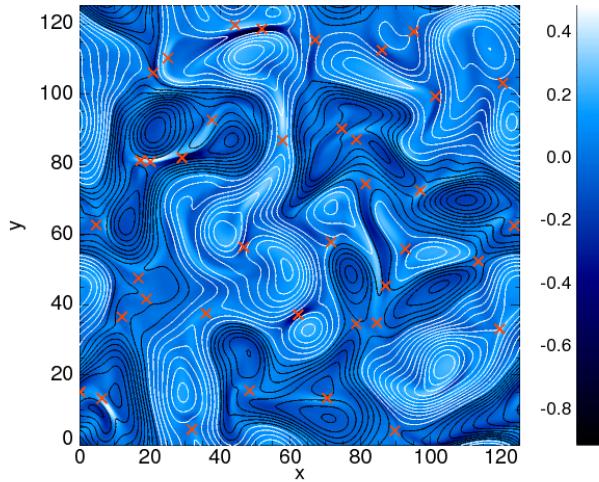


Figure 2: Contour plots of out-of-plane total current density. The isolines of the magnetic potential are indicated by black/white lines. The positions of the X-points, where the reconnection occurs, are indicated by red thick crosses.

The system size in the spatial domain is  $L = 2\pi \times 20$  in both  $x$  and  $y$  directions, where periodic boundary conditions are imposed; while in the velocity domain we fix  $v_{max,i} = \pm 5v_{th,i}$ , for both ion species ( $i = p, \alpha$ ), in each velocity direction. In these simulations, we use  $512^2$  gridpoints in the two-dimensional spatial domain and  $61^3$  and  $31^3$  gridpoints in proton and alpha particle three-dimensional velocity domains, respectively.

We study the plasma dynamics and the development of turbulence in the periodic plane perpendicular to the ambient magnetic field. In order to quantify the turbulent activity in the system, we compute the power spectra of density (green-square line) and bulk velocity (purple-triangle line) for alpha particles and of magnetic (black-solid line) and electric fields (red-dashed line), shown in Fig. 1 for four different times ( $t = 1$  (a),  $t = 10$  (c) and  $t = 40$  (e)) during the simulations. At the same times, we display also in Fig. 1 the temperature anisotropy for alpha particles [(b)-(d)-(f)], defined as the ratio between the perpendicular and parallel temperature, with respect the local magnetic field ( $A_\alpha = T_\perp^{(\alpha)} / T_\parallel^{(\alpha)}$ ). A direct comparison clearly indicates that, in the early stage of the system evolution (a)-(b), when the energy is stored at large scales, the PDF is picked around  $A_\alpha = 1$ , meaning that the simulation starts with an isotropic configuration. During the evolution of the system (c)-(d), when the energy is transferred at short scales and the turbulent spectrum occurs, the PDF elongates in the parallel ( $A_\alpha < 1$ ) and in the perpendicular ( $A_\alpha > 1$ ) direction, displaying a strong anisotropic behavior, that reaches his maximum value at  $t = 40$  (e)-(f). It is worth nothing that the temperature anisotropy appears to be a direct effect of

the turbulent nature of the system.

The turbulent activity leads to the generation of coherent structures, which can be identified as vortices and current sheets. This behavior can be seen in the shaded contour map (Fig. 2) of the out-of-plane total current density. Since the current density is proportional to the level of small-scale gradients, it represents a good indicator of the level of turbulent activity. The observed coherent structures are not static but, during the dynamical evolution of the system, interact nonlinearly among each others. In between the island, the current becomes very intense and reconnection events locally occur at the X points of the magnetic potential, indicated in the contour plot by red crosses. The presence of these high magnetic stress regions is a signature of the intermittent nature of the magnetic field, that affects the patchiness of the parallel and perpendicular ion heating.

Recently, Perrone et al. [7] have reported that in kinetic simulations the temperature anisotropy of alpha particles is correlated to the proton temperature anisotropy, a property which is also observed in solar wind [8]. Our analysis shows that this correlation is determined by the fact that both PDFs are modulated by the ambient magnetic field, inside those regions where the high magnetic stresses discussed above are present. In conclusion the kinetic dynamics of the ion distribution functions appears to be directly determined by the turbulent activity of the plasma system.

The numerical simulations discussed in this paper were performed on the FERMI supercomputer at CINECA (Bologna, Italy), within the European project PRACE Pra04-771. D.P. is supported by the Italian Ministry for University and Research (MIUR) PRIN 2009 funds (grant number 20092YP7EY).

## References

- [1] R. Bruno and V. Carbone, LRSP **2**, 4 (2005); E. Marsch, LRSP **3**, 1 (2006)
- [2] E. Marsch, K.-H. Mühlhäuser, R. Schwenn, et al., J. Geophys. Res. **87**, A1 (1982)
- [3] E. Marsch, K.-H. Mühlhäuser, R. Schwenn, et al., J. Geophys. Res. **35**, A1 (1982)
- [4] J.C. Kasper, A.J. Lazarus and S.P. Gary, Phys. Rev. Lett. **101**, 261103 (2008)
- [5] F. Valentini, P. Trávníček, F. Califano et al., J. Comput. Phys. **225**, 753 (2007)
- [6] D. Perrone, F. Valentini and P. Veltri, Astrophys. J. **741**, 43 (2011)
- [7] D. Perrone, F. Valentini, S. Servidio et al., Astrophys. J. **762**, 99 (2013)
- [8] B.A. Maruca, J.C. Kasper and S.P. Gary, Astrophys. J. **748**, 137 (2012)